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Original communication

Estimation of stature using anthropometry of feet and footprints in a Western Australian population

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A B S T R A C T

The aim of the study is to develop accurate stature estimation models for a contemporary Western Australian population from measurements of the feet and footprints. The sample comprises 200 adults (90 males, 110 females). A stature measurement, three linear measurements from each foot and bilateral footprints were collected from each subject. Seven linear measurements were then extracted from each print. Prior to data collection, a precision test was conducted to determine the repeatability of measurement acquisition. The primary data were then analysed using a range of parametric statistical tests. Results show that all foot and footprint measurements were significantly ($P < 0.01-0.001$) correlated with stature and estimation models were formulated with a prediction accuracy of ±4.673 cm to ±6.926 cm. Left foot length was the most accurate single variable in the simple linear regressions (males: ±5.065 cm; females: ±4.777 cm). This study provides viable alternatives for estimating stature in a Western Australian population that are equivalent to established standards developed from foot bones.

1. Introduction

An important component of the forensic anthropologist's role in medico-legal investigations is contributing towards the identification of the deceased, but increasingly in a modern global society, identification of the living. As part of this process the forensic anthropologist will develop a biological profile to narrow down the parameters of identity, of which age, sex, stature and ancestral affinity are the primary attributes.[1]

In continuation of a large scale research project aiming to devise Australian forensic anthropological standards, the specific aim of the present study is to examine bilateral asymmetry of foot and footprint measurements in a contemporary Western Australian population and to develop stature estimation models on the basis of those measurements. Although not included in the original research aims, the opportunity to analyse the difference between self-reported height and measured stature was an interesting outcome of the data collection procedure.

In the majority of medico-legal cases that come before a forensic anthropologist the most delimiting of the aforementioned parameters for biological identity are age and sex. In cases, however, where isolated fleshed body parts are encountered, estimates of stature may be the most practical point at which to begin the identification process, especially in the adult foot (for which age and ethnicity markers are largely absent). The latter cases are admittedly infrequent, but they do occur, especially in multiple-fatality (DVI or forensic), scenarios where dismemberment (e.g., anthropomorphic or postmortem) of a number of individuals is encountered. Further, footprints can also be recovered as impressions in mass graves, or at domestic crime scenes, where offenders have been known to leave footprint evidence. Krishan[2] advocates the analysis of barefoot impressions for developing countries such as India, where the majority of the rural population rarely wear shoes due to socio-economic and climatic factors. A similar argument can be made for other countries, including, but not limited to, Australia.

Traditionally, the study of documented skeletal collections has been used as a benchmark for developing standards to estimate the key biological indicators of identity. This approach, however, is limited to some degree, as the most accurate results are achieved when those standards are applied to individuals belonging to the same the population from which they are formulated.[3] Average stature between different population groups can vary by more than 30 cm.[4] Final adult stature is influenced by complex interactions

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between a number of genetic and environmental factors.[5,6] As such, where possible, application of contemporary population specific standards are preferable to generic standards. In addition, many documented skeletal collections are comprised of non-contemporary individuals, and are thus not representative of secular changes that are known to have since occurred in modern populations, particularly in regard to stature.[7] Populations are dynamic, which means stature estimation standards should be constantly revised, thus ensuring the most accurate estimations are made.

Anthropometry is an invaluable tool for developing population specific standards for the biological profiling of unidentified deceased and living individuals.[8–10] Whilst osteometry is most commonly associated with forensic practice,[11,12] standards are being developed from modern living populations (e.g. India,[13–15] Egypt,[16] and Australia[17,18]), thereby overcoming some of the limitations of those skeletal collections that are temporally and genetically 'static'. The study of contemporary samples in this manner can provide Australian forensic practitioners with accurate and defensible means to establish a biological profile. Previous research into this area has been conducted in countries outside of Australia, with many of the most recent studies coming from India. As modern India has one of the largest and most ethnically diverse populations in the world[15] it presents numerous opportunities to study anthropometric variation, particularly genetically isolated indigenous groups.

Krishan and Sharma[13] analysed hand and foot measurements in a young (17–20 years) sample of 246 (123 males; 123 females) Rajputs – an endogamous caste group of North India. They found that foot measurements were significantly correlated ($P < 0.001$) with stature and males were significantly larger ($P < 0.01$) than females for all measurements. Kanchan et al.[19] examined foot dimensions in a sample comprising 200 Gujjar (another North Indian endogamous caste group) individuals equally distributed by sex and ranging in age from 18 to 80 years. Although they divided their sample into two age groups (< 30 > years), age was not found to have any significant correlation to stature. Males were significantly larger ($P < 0.001$) than females for all dimensions and a series of stature estimation models were presented, with associated error rates of ±3.077 cm to 5.440 cm.

In a comprehensive study, Krishan further investigated the relationship between foot size and stature in a sample of 1040 male Gujjars between the ages of 18–30 years. A total of seven bilateral foot measurements,[14] and 10 bilateral measurements from bare footprint impressions,[2] were analysed. Tests for bilateral asymmetry revealed that T1, T2 and T5 lengths were significantly larger on the left side ($P < 0.01$). T1 length had the highest correlation with stature ($r = 0.86$) for both sides. Sen and Ghosh[15] developed stature estimation formulae based their analysis of a sample of 350 'adult' Rajbanshi (a Schedule Caste group from North Bengal), equally distributed by sex. Rajbanshi males were significantly larger ($P < 0.05$) than females for all variables. For both sexes left foot measurements were found to be larger than the right, although this difference was only significant for foot length ($P < 0.05$). Left foot length had the highest correlation with stature for the pooled sample ($r = 0.811$); for males it was right foot length ($r = 0.624$); and for females, both left and right foot length produced the same coefficient ($r = 0.682$). When the sample is split according to sex, age is reported to have a low negative correlation ($r = -0.114$ for males; -0.118 for females) with stature, although it was not indicated if was statistically significant. The models were then tested on a group of a 100 Meche (50 males, 50 females) individuals; a smaller, but ethnically distinct, indigenous community from the same region. When the equations for the estimation of stature from multiple and linear regression equations obtained for the Rajbanshi are applied to the Meche, the accuracy rate varied widely (males 94.78–102.34%; females 93.90–99.40%) and were thus deemed to be too inaccurate for use in this population.

Fawzy and Kamal[16] examined a small sample (50) of young (18–25 years) Egyptian male medical students. A total of nine bilateral footprint measurements were taken; all variables (except footprint breadth) were found to be significantly larger ($P < 0.01$) on the left side. Unlike previous studies, however, a number of variables were not significantly correlated with stature, including left footprint breadth, left and right heel breadth, and all big toe measurements. Another anomalous result was that right T5 length had the highest correlation ($r = 0.58$) with stature and the lowest SEE (±3.55 cm) for the simple linear regression equations. Left and right T1 lengths produced similarly accurate results ($r = 0.54$; SEE ±3.55 cm for right, ±3.63 cm for left) which was comparable to previous research. Whilst Fawzy and Kamal's research has made an important contribution to forensic anthropology population data in regard to stature estimation from footprints, there are limitations to the study, including a small sample size, narrow age range and selection bias in using only male medical students.

Aside from bilateral asymmetry, there are known limitations to the collection of actual and reported stature data. The progressive loss of living height over one's lifetime is known to occur, although the literature is divided when it comes to applying these age-related differences to stature estimations made from foot and footprint measurements; previous research has demonstrated a significant age related change in stature,[20] whereas other research has not affirmed this claim.[15] Irrespective, age corrections to stature estimation is more exclusive than beneficial in fragmentary remains, due to the inability to accurately estimate age in adult feet or footprints. Age is, therefore, of limited forensic utility when estimating stature from isolated feet and footprints. Similarly, diurnal variation in living stature has been reported in the literature, the average reported daily loss in stature is 0.98 ± 0.2 cm[21] and the majority of that loss in height occurs rapidly after rising (30 min–2 h).[22] Due to the relatively small loss anticipated during the study period (9 am–5 pm) and the difficulty of collecting data at the same time-points across a large sample, diurnal variation is not controlled in the present study.

On examining self-reported statures in 8000 US military personnel, Giles and Hutchinson[23] found that on average males overestimated their stature by 2.5 cm and females by 1 cm. Spencer et al.[24] reported similar results in their study of 4808 British subjects, where males over-reported by 1.23 cm and females by 0.6 cm. However, Krul et al.[25] examined self-reported measures of individuals from North America, Italy and the Netherlands, and found that overall males overestimated their height by 1.7 cm and females by 1.1 cm. Yet when they examined the individual population groups, they found that the Italian sub-group had the largest amount of over-reporting, and that within this group, females actually overestimated their height more than males. Conversely, a Scottish study found that both males and females underestimated their height; males by 1.3 cm and females by 1.7 cm.[26] Thus, trends in self-reported height depend on a host of factors, including age,[23,24,27] population affinity,[28] actual height, and even self-perceptions of masculinity.[29] The present study was able to quantify the error in reported stature in the Western Australian sample population.

2. Materials and methods

2.1. Materials

Measurements for this study were taken from a sample comprising 200 adult residents of Western Australia (90 male; 110 female) by one observer (NH). Subjects were predominantly recruited from the staff and student population of the University of

Western Australia and the enlisted and civilian staff of the Western Australian Police service. Only subjects 18 years and older were invited to participate in the study. Data collection occurred between August and November 2009 (winter and spring). Participating subjects were required to sign a combined information sheet and consent form. Basic demographic data (e.g. age, sex, perceived ethnicity) was collected via a questionnaire that was completed by the subject at the time of measurement. The questionnaires were anonymised to protect participant privacy.

The ethnic affiliations of individuals in the study were found to be representative of the Western Australian population as a whole,[30] which is predominantly Caucasian. The sample consisted of individuals aged between 18 and 68 years; the mean age for male individuals is 38.2 years (range 19–68 years) and the mean female age is 36.5 (range 18–63 years). Any subjects with obvious abnormalities of the foot, or pathology of the back, hip and knee affecting stature, were excluded from the study. Ethical approval to undertake this study was provided by the Human Research Ethics Committee of the University of Western Australia (RA/4/1/2382).

2.2. Methods

2.2.1. Footprint acquisition

A *Podograph* (Ruckgaber Orthopädie Service) was used to acquire the footprints. This podiatric footprinting device consists of two plates for the left and right feet, each covered by a framed rubber membrane that slides and rotates on an internal hinge. The podograph is designed so that an inked membrane only makes contact with underlying paper when a load-bearing foot applies pressure. To obtain the most accurate representation of static footprints, the left and right sides are taken independently. The membranes are then inverted to check the quality of the prints, specifically that all the necessary landmarks are present. If the print is not of suitable quality, the subjects were asked to repeat the procedure. Even after attempting a number of repeat prints, impressions of the fifth digit were still not visible for some subjects (and second digit for one subject); hence not all measurements were able to be taken in those individuals.

2.2.2. Measurements

Stature (living height) was measured using a stadiometer (Seca 204); each subject was asked to stand bare-footed on the flat platform, with heels placed together and touching the base of the vertical board. The head was positioned in the Frankfort Horizontal (FH) plane against the vertical board; the subject was requested to maintain an erect position with their back in contact with the vertical board and arms placed on the side of the thigh. The horizontal sliding bar is positioned on the contact point of the vertex of the head and stature is recorded in centimetres.[31]

Three anthropometric measurements were taken on each foot. Maximum length was acquired using an osteometric board (Paleo-Tech Concepts, Inc.). The subject was required to stand in a relaxed stance with their weight evenly distributed between both feet, with the foot to be measured positioned on the osteometric board and the other placed a short distance apart, but at a similar level. The two width measurements were taken using digital calipers (Mitutoyo 700-128; stated accuracy ±0.1 mm) whilst in this same relaxed stance. Seven measurements were taken from the footprint with a Staedtler® Mars® reduction scale ruler with accuracy confirmed using the Mitutoyo digital caliper (see above). All measurements are defined in Table 1 and illustrated in Fig. 1.

2.2.3. Statistical analyses

A precision study was performed prior to primary data collection; stature, foot and footprints of the same four subjects were measured on four different evaluation days, with a minimum of 24-h between re-measurement. Intra-observer error was determined to be within accepted standards for all measurements ($R > 0.75$; rTEM $< 5\%$).[32–34] With the exception of heel breadth ($R = 0.878$; 0.932), all measurements complied with the stricter threshold ($R > 0.95$) recommended by Ulijaszek and Kerr.[8]

Table 1
Definition of measurements used in the present study.

Measurement	Definition
Stature	The maximum standing height from feet to vertex.
Anthropometric measurements	
Foot Length (FL)	The maximum distance between the heel (pternion) and longest toe (akropodian).
Foot Breadth (FB)	The distance between the most prominent point on the medial side of the foot to the most prominent point on the lateral side (which corresponds to the heads of the first to fifth metatarsals).
(Foot) Heel Breadth (FHB)	The maximum distance from the most protruding point on the medial surface of the heel to the corresponding protrusion on the lateral surface of the heel.
Measurements from footprints	
Heel-Toe Lengths (FPT1L – FPT5L)	The distance between the most distal point of each toe to the pternion.
Breadth (FPB)	The distance between the most lateral and the most medial projecting points of the margins of the forefoot region of the footprint (corresponds to the most prominent areas of the metatarsal-phalangeal joints).
Heel Breadth (FPHB)	The widest distance across the ball of the heel.

The measurement data was subjected to normal descriptive statistics, then evaluated for bilateral asymmetry using a paired samples *t*-test. Sex-specific left and right foot and footprint measurements were subjected to simple linear regression analysis; accuracy is quantified using standard errors of the estimate. Multiple regression analysis was performed to assess whether prediction accuracy improved from the simple linear formulae. Statistical analyses were performed using *IBM® SPSS® Statistics 19* predictive analytics software.

3. Results

3.1. Stature and self-reported stature

A total of 195 subjects (87 male, 108 female) provided a self-reported stature figure, (e.g., what they believed their height to be). On average, both males and females overestimated their

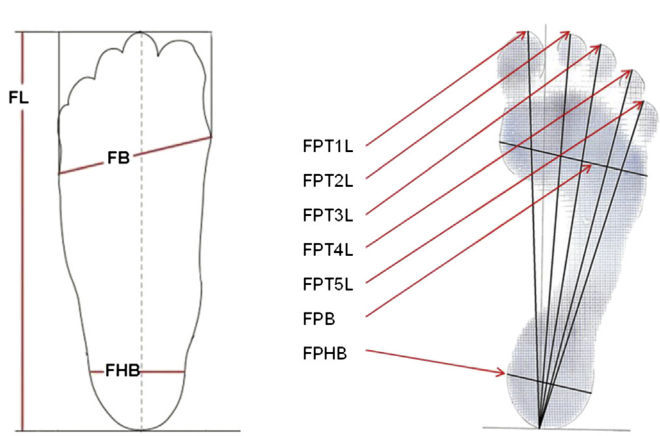

Fig. 1. Diagram of foot (left) and podograph (right) images indicating measurements described in Table 1.

Table 2
Measured and self-reported stature (cm) including results of the paired *t*-test for significance of difference.

	n	Descriptive statistics (cm)				Paired *t*-test		
		Min.	Max.	Mean	SD	Mean diff.	*t*-score	*P*-Value
Male								
Measured	90	162.4	200.5	178.47	7.08			
Self-reported	87	162.0	203.0	179.51	7.03	1.04	3.628	***
Female								
Measured	110	149.4	191.3	163.67	7.14			
Self-reported	108	144.0	193.0	163.74	7.87	0.17	0.608	NS

Significance: $^{***}P < 0.001$, NS = not significant.

stature (Table 2); males by +1.04 cm and females by +0.17 cm. The difference between measured and self-reported height was statistically significant for males ($P < 0.001$).

3.2. Descriptive statistics and bilateral asymmetry

The mean male measured stature was 178.47 cm (SD 7.08; range 162.4–200.5 cm) and for females it was 163.67 cm (SD 7.14; range 149.4–191.3 cm). The mean, standard deviation and correlation to stature for each of the ten foot and footprint measurements (left and right for both sexes) are shown in Table 3.

Bilateral asymmetry was found to be very small. Male foot length (FL) and heel breadth (FHB) were significantly larger on the left than the right side ($P < 0.01$ and < 0.05 respectively), albeit with an actual difference of less than 1 mm. For the footprint dimensions, all male heel-toe lengths (T1FPL–T5FPL) were significantly larger on the left side ($P < 0.05$–0.001). For females, left T1 length (T1FPL) and right heel breadth (FPHB) were significantly larger. Again, these differences were small, amounting to less than 2 mm.

3.3. Simple linear regression

3.3.1. Foot measurements

Simple linear regression models were calculated to explore the relationship between stature and foot dimensions. Left foot length had the highest correlation and the smallest standard error of the estimate (SEE) (males: ±5.065 cm; females: ±4.777 cm) followed by right foot length (see Table 4). Foot heel breadth was the least accurate variable for estimating stature with the largest SEE (±6.703 cm for left heel breadth in females). A similar range of accuracy was observed for the remaining male (±5.065 to ±6.543 cm) and female (±4.777 to ±6.651 cm) models (Table 4).

3.3.2. Footprint measurements

For the analysis of footprint measurements (Table 5), the SEE values ranged between ±4.885 cm (male left T2 length) and ±6.926 cm (female left heel breadth). In males, left T1–T4 heel-toe lengths were more accurate for predicting stature (SEE: ±4.885 to ±5.064 cm) than any of the right heel-toe lengths (SEE: ±5.198 to ±5.404 cm). The most accurate right side measurement for estimating stature was T4 heel-toe length (SEE: ±5.198 cm). For females, T1 length had the smallest error (right ±5.006 cm, left ±5.161 cm).

3.4. Multiple regression

3.4.1. Foot measurements

Direct multiple regression analyses were performed to determine the most accurate models for predicting stature; the four most accurate equations in each category are presented in Table 6. The smallest SEE for the anthropometric foot measurements was ±4.673 cm (females) and ±5.064 cm (males); both of those equations use the combination of left foot length and left foot heel breadth.

3.4.2. Footprint measurements

Multiple regression equations of footprint measurements for males and females are presented in Table 7. The most accurate equation in males involved the combination of all five left heel-toe lengths (SEE ±4.846 cm). In the female sample the most accurate model was the one that incorporated all seven measurements (SEE ±4.709 cm). Overall the SEE's for the footprint measurements are slightly lower than the accuracy achieved using measurements of the fleshed foot (Tables 6 and 7).

4. Discussion

4.1. Self-reported height

Determining the accuracy of self-reported height data is important forensically because often the only reliable source for missing person reports is information obtained from government and medical records, or the testimony of family and friends. Those records and/or testimony, however, are all rarely based on a professional measurement. In the former situation stature is likely to be verbally communicated (e.g., during a routine medical consultation). As such, forensic researchers are interested in whether it is possible to accurately account for differences between self-reported and measured stature.[23] Aside from the forensic

Table 3
Descriptive statistics for foot and footprint measurements (in cm) in males and females.

	Male						Female					
	Left			Right			Left			Right		
	Mean	SD	*r*	Mean	SD	*r*	Mean	SD	*r*	Mean	SD	*r*
Foot												
FL	27.42	1.38	0.70	27.34	1.36	0.70	24.58	1.22	0.75	24.56	1.21	0.74
FB	10.34	0.63	0.42	10.36	0.63	0.40	9.27	0.58	0.42	9.28	0.55	0.38
FHB	6.79	0.49	0.41	6.75	0.49	0.40	6.01	0.46	0.36	6.03	0.45	0.37
Footprint												
FPT1L	25.48	1.33	0.71	25.34	1.33	0.68	23.01	1.17	0.69	22.94	1.19	0.72
FPT2L	25.46	1.34	0.73	25.32	1.37	0.67	22.87	1.23	0.66	22.86	1.18	0.65
FPT3L	24.49	1.32	0.70	24.37	1.35	0.67	22.07	1.16	0.66	22.05	1.13	0.64
FPT4L	23.15	1.27	0.72	23.06	1.29	0.68	20.89	1.05	0.68	20.90	1.03	0.65
FPT5L	21.29	1.16	0.68	21.23	1.20	0.65	19.30	0.94	0.68	19.27	0.96	0.70
FPB	9.95	0.63	0.44	9.96	0.62	0.44	8.97	0.57	0.39	9.00	0.54	0.31
FPHB	5.59	0.46	0.51	5.57	0.49	0.43	5.06	0.46	0.26	5.11	0.44	0.30

Key: Definition of measurements in Table 1 and Fig. 1.

Table 4
Linear regression equations for estimation of stature (in cm) from measurements of the foot on the left and right side.

Male			Female		
Equation	SEE	*r*	Equation	SEE	*r*
Left			*Left*		
$S = 79.839 + 3.597(FL)$	5.065	0.703	$S = 56.375 + 4.365(FL)$	4.777	0.746
$S = 129.442 + 4.739(FB)$	6.453	0.423	$S = 115.292 + 5.218(FB)$	6.495	0.424
$S = 138.145 + 5.938(FHB)$	6.488	0.412	$S = 130.283 + 5.551(FHB)$	6.703	0.355
Right			*Right*		
$S = 78.913 + 3.642(FL)$	5.105	0.697	$S = 56.476 + 4.364(FL)$	4.841	0.738
$S = 131.858 + 4.500(FB)$	6.524	0.401	$S = 117.865 + 4.935(FB)$	6.631	0.380
$S = 140.198 + 5.672(FHB)$	6.543	0.395	$S = 127.823 + 5.949(FHB)$	6.651	0.373

Key: Definition of measurements in Table 1 and Fig. 1; S = stature.

implications, a number of public health researchers have also examined the accuracy of self-reported height and weight measures due to the potential impact it has on BMI (body mass index) reporting.[27]

The results of the present study replicated the findings of previous research, whereby both males and females over-report their stature, but males by a greater amount. Clearly, the results of the present study have provided further support that self-reported height data needs to be approached cautiously, although in many instances, the confidence interval of a stature prediction will make sufficient provision for the magnitude of correction needed.[35]

4.2. Foot measurements

In the present study males were found to have significant (albeit metrically small) bilateral asymmetry in foot measurements, with the left side being larger than the right; whereas for females there was no significant asymmetry. This pattern, however, is not consistent across all population groups. Krishan and Sharma[13] found no significant asymmetry for either male or female groups, and Krishan's[14] study of male Gujjars showed that right foot breadth was larger (although non-significant) and a number of length measurements were significantly larger on the left side. Sen and Ghosh[15] found that both males and females had significantly larger left foot lengths, however other studies (e.g., Krishan and Sharma,[13] Krishnan,[13,14] Kanchan et al.[19]) found that females displayed no significant bilateral asymmetry.

All foot measurements in this study correlate with stature; left foot length had the strongest correlation in both sexes. Left foot length was also found to be the most accurate single variable for estimating stature in both males (SEE: ±5.065 cm) and females (SEE: ±4.777), whilst heel breadth was the least accurate individual variable. Direct multiple regression formulae marginally improved upon the accuracy of the linear equations for males (SEE: ±5.095) and females (SEE: ±4.673, Table 6).

As anticipated, the stature estimation formulae from the present study are not as accurate as the Turkish and Indian studies for which comparative SEE's are available; the standards from those studies were developed on genetically homogenous populations, including endogamous caste groups of North India. However, the results of the present study are more similar to Giles and Vallandigham's[36] investigation of US military personnel, which found that right foot length can be used to estimate stature with an accuracy of ±4.856 cm for males and ±4.700 cm for females. Although conducted on a much larger scale, the sample population would have a similar ethnic diversity as the Western Australian population examined in this project.

With regard to the multiple regression equations, a number of the aforementioned studies combined foot measurements with hand measurements, or foot measurements with footprint measurements. Notable exceptions include the Krishan and Sharma[13] study of Rajputs, which provide multiple regression formulae incorporating left foot length and breadth. Their multiple regression models are considerable more accurate compared to those using single measurements, with their most accurate models providing a SEE of ±3.02 cm for males and ±2.98 cm for females. In addition, the Kanchan et al.[19] study of Gujjars also provides multiple regression equations exclusively for the feet. In this instance, however, equations that combine both length and breadth

Table 5
Linear regression equations for estimation of stature from measurements (in cm) of footprints on the left and right side.

Male			Female		
Equation	SEE	*r*	Equation	SEE	*r*
Left			*Left*		
$S = 82.720 + 3.757(FPT1L)$	5.044	0.706	$S = 66.030 + 4.243(FPT1L)$	5.161	0.694
$S = 80.282 + 3.856(FPT2L)$	4.885	0.728	$S = 76.440 + 3.813(FPT2L)$	5.391	0.659
$S = 85.752 + 3.785(FPT3L)$	5.064	0.703	$S = 73.841 + 4.071(FPT3L)$	5.374	0.662
$S = 84.905 + 4.041(FPT4L)$	4.920	0.723	$S = 66.870 + 4.633(FPT4L)$	5.229	0.684
$S = 90.398 + 4.137(FPT5L)$	5.235	0.678	$S = 63.792 + 5.174(FPT5L)$	5.232	0.684
$S = 129.565 + 4.913(FPB)$	6.414	0.435	$S = 120.797 + 4.779(FPB)$	6.617	0.385
$S = 135.222 + 7.737(FPHB)$	6.140	0.507	$S = 143.358 + 4.014(FPHB)$	6.926	0.259
Right			*Right*		
$S = 87.054 + 3.608(FPT1L)$	5.232	0.678	$S = 64.985 + 4.302(FPT1L)$	5.006	0.716
$S = 91.069 + 3.451(FPT2L)$	5.297	0.668	$S = 74.144 + 3.916(FPT2L)$	5.473	0.646
$S = 93.394 + 3.491(FPT3L)$	5.315	0.666	$S = 74.050 + 4.064(FPT3L)$	5.489	0.643
$S = 91.824 + 3.758(FPT4L)$	5.198	0.684	$S = 69.484 + 4.506(FPT4L)$	5.447	0.650
$S = 96.762 + 3.848(FPT5L)$	5.404	0.652	$S = 63.345 + 5.205(FPT5L)$	5.115	0.701
$S = 127.787 + 5.089(FPB)$	6.380	0.444	$S = 126.847 + 4.091(FPB)$	6.822	0.307
$S = 143.849 + 6.220(FPHB)$	6.439	0.427	$S = 139.344 + 4.764(FPHB)$	6.849	0.296

Key: Definition of measurements in Table 1 and Fig. 1; S = stature.

Table 6
Multiple regression equations from foot measurements (cm) for stature estimation in males and females.

Sex	Foot	Equation	SEE (±cm)	r
Male	Left	$S = 81.099 + 4.031(LFL) - 0.443(LFB) - 1.263(LFHB)$	5.089	0.708
		$S = 81.549 + 3.849(LFL) - 0.833(LFB)$	5.078	0.705
		$S = 80.254 + 3.952(LFL) - 1.493(LFHB)$	5.064	0.707
		$S = 124.592 + 2.991(LFB) + 3.378(LFHB)$	6.367	0.458
	Right	$S = 81.099 + 4.257(RFL) - 1.057(RFB) - 1.193(RFHB)$	5.106	0.705
		$S = 81.376 + 4.062(RFL) - 1.348(RFB)$	5.095	0.703
		$S = 79.254 + 4.025(RFL) - 1.602(RFHB)$	5.099	0.702
		$S = 125.708 + 2.859(RFB) + 3.431(RFHB)$	6.421	0.443
Female	Left	$S = 55.726 + 5.081(LFL) + 0.521(LFB) - 3.623(LFHB)$	4.673	0.764
		$S = 57.994 + 4.603(LFL) - 0.805(LFB)$	4.785	0.747
		$S = 113.345 + 4.188(LFB) + 1.911(LFHB)$	6.494	0.433
	Right	$S = 57.532 + 4.814(RFL) - 0.060(RFB) - 1.918(RFHB)$	4.836	0.744
		$S = 58.615 + 4.553(RFL) - 0.730(RFB)$	4.852	0.739
		$S = 57.373 + 4.806(RFL) - 1.952(RFHB)$	4.813	0.744
		$S = 113.623 + 3.110(RFB) + 3.514(RFHB)$	6.549	0.416

Key: Definition of measurements in Table 1 and Fig. 1; S = stature.

Table 7
Multiple regression equations for estimation of stature (in cm) in males and females from measurements of footprints on the left and right side.

Sex	Equation	SEE (±cm)	r
Male	*Left footprint*		
	$S = 79.530 + 1.139(LFPT1L) + 3.009(LFPT2L) - 2.683(LFPT3L) + 4.514(LFPT4L) - 2.138(LFPT5L)$	4.846	0.746
	$S = 82.654 + 0.977(LFPT1L) + 3.223(LFPT2L) - 2.743(LFPT3L) + 4.878(LFPT4L) - 2.544(LFPT5L) - 0.951(LFPB) + 1.197(LFPHB)$	4.880	0.752
	$S = 78.175 + 1.129(LFPT1L) + 2.809(LFPT2L)$	4.882	0.732
	$S = 78.411 + 1.065(LFPT1L) + 2.732(LFPT2L) + 0.603(LFPHB)$	4.905	0.732
	Right footprint		
	$S = 85.649 + 2.267(RFPT1L) - 0.259(RFPT2L) - 0.637(RFPT3L) + 3.354(RFPT4L) - 0.935(RFPT5L)$	5.225	0.699
	$S = 86.158 + 2.320(RFPT1L) + 1.324(RFPT2L)$	5.228	0.684
	$S = 91.595 + 3.534(RFPT4L) + 0.254(RFPT5L)$	5.232	0.684
	$S = 85.988 + 2.307(RFPT1L) - 0.070(RFPT2L) + 1.468(RFPT3L)$	5.237	0.687
Female	*Left Footprint*		
	$S = 52.239 + 2.905(LFPT1L) + 0.691(LFPT2L) - 2.199(LFPT3L) + 1.671(LFPT4L) + 2.321(LFPT5L) + 1.633(LFPB) - 3.369(LFPHB)$	4.979	0.738
	$S = 56.195 + 2.810(LFPT1L) + 0.260(LFPT2L) - 2.761(LFPT3L) + 2.917(LFPT4L) + 1.908(LFPT5L)$	5.070	0.720
	Right Footprint		
	$S = 53.050 + 4.693(RFPT1L) - 2.536(RFPT2L) + 0.698(RFPT3L) - 2.553(RFPT4L) + 5.276(RFPT5L) + 1.568(RFPB) - 3.309(RFPHB)$	4.709	0.771
	$S = 59.453 + 4.462(RFPT1L) - 3.397(RFPT2L) + 1.454(RFPT3L) - 2.608(RFPT4L) + 5.291(RFPT5L)$	4.784	0.756

Key: Definition of measurements in Table 1 and Fig. 1; S = stature.

measurements show only a small improvement (±0.017 to ±0.165 cm) over single variable equations, and in one instance (male left side equation), accuracy actually decreased by ±0.018 cm.

Compared to osteometric research, the prediction accuracy of the Western Australian standards (SEE: ±4.673 to ±6.703 cm) are equivalent to those developed for metatarsal[37] (SEE: ±3.99 to ±7.60 cm), calcaneus and talus[38] measurements (SEE: ±4.13 cm to ±6.25 cm). Both studies were based on samples of African and European American documented skeletons and the most accurate equations were ancestry specific. When ancestry was pooled (but sex known) the error rates increased to ±5.48 cm to ±7.38 cm for the metatarsal standards and ±4.72 cm to ±6.07 cm for the calcaneus and talus. This again demonstrates that the more certain an investigator is about ancestral affiliation, the more accurate they are likely to be in their estimations of other biological characteristics. Unfortunately, in a culturally diverse society such as Australia, it is doubtful that standards will be developed at the sub-population group level, particularly for anatomical regions that are unlikely to reveal ancestral affiliation.

4.3. Footprint measurements

In the present study there was sufficient significant bilateral asymmetry in footprints across all groupings to warrant side specific equations. As with foot measurements, males displayed greater asymmetry and all lengths were larger on the left side. For the females, only left T1 length was significantly larger, whereas footprint heel breadth was significantly larger on the right side. The Fawzy and Kamal[16] study of Egyptian male individuals supports this finding, in that all length measurements, in addition to footprint heel breadth, are significantly larger on the left side. North Indian Gujjars[2] T2 and T5 lengths are also significantly larger on the left side.

All footprint dimensions were significantly correlated with stature and the heel-toe lengths had the strongest correlation ($r = 0.643$–0.728) across all groupings. Unlike foot measurements, however, there was no one particular variable that consistently displayed the largest correlation coefficient. For males, left T2 length was the most accurate single variable ($r = 0.728$; SEE: ±4.885 cm) and for females it was right T1 length ($r = 0.716$; SEE: ±5.006 cm). Overall, the simple linear regression equations had an SEE that ranged from ±4.885 to ±6.926 cm. Heel-toe lengths were more accurate (SEE: ±4.885 to ±5.489 cm) than any of the breadth measurements (SEE: ±6.140 to ±6.926 cm). The multiple regression analysis indicated that addition of some variables improved upon the accuracy of the single variable equations for males (SEE: ±4.846 cm) and females (SEE: ±4.709 cm). The most accurate (SEE: ±4.709 cm) equation included all seven footprint measurements.

5. Conclusions

This study has demonstrated the utility and reliability of stature estimation standards developed from foot and footprint measurements in a sample from a contemporary Western Australian

population. A series of statistically quantified stature estimation standards are outlined with accuracies starting from ±4.673 cm. The impetus for this research is due to an ongoing project by the Centre for Forensic Science at the University of Western Australia to develop biological profiling protocols for a Western Australian population without the need to rely on large, documented skeletal collections. Anthropometry, along with virtual imaging technologies (CT scans, radiographs) are all part of an innovative approach to expanding forensic anthropological research into realms that are applicable to a contemporary Australian population.

Ethical approval

Ethical approval to undertake this study was provided by the Human Research Ethics Committee of the University of Western Australia (RA/4/1/2382).

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Conflict of interest

None declared.

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